Low-Thrust Trajectory Maps (Bacon Plots) to Support a Human Mars Surface Expedition

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Problem statement

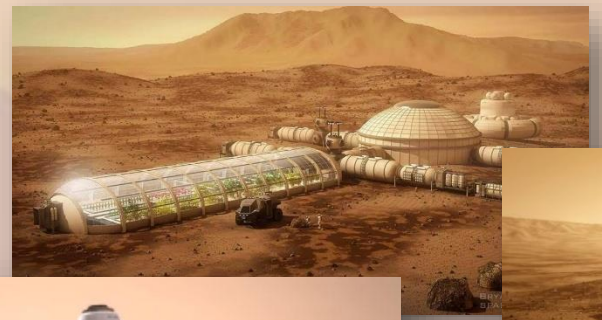
Common goal: Humans on Mars

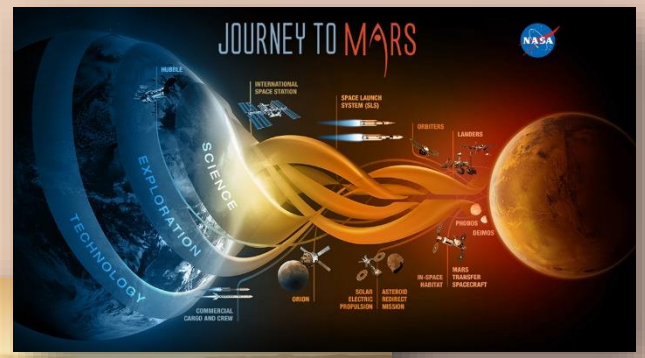
Mission Design Problem: How to orchestrate a viable mission sequence to deliver the required elements

Fact: Porkchop plots are useful tools for early planning of ballistic trajectories

Fact: Solar Electric Propulsion is very efficient and useful for cargo delivery

Potential solution: Use SEP tugs to deliver cargo and logistics, with bacon plots as a map and planning tool

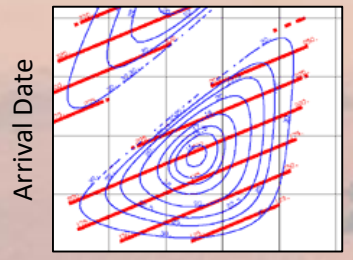


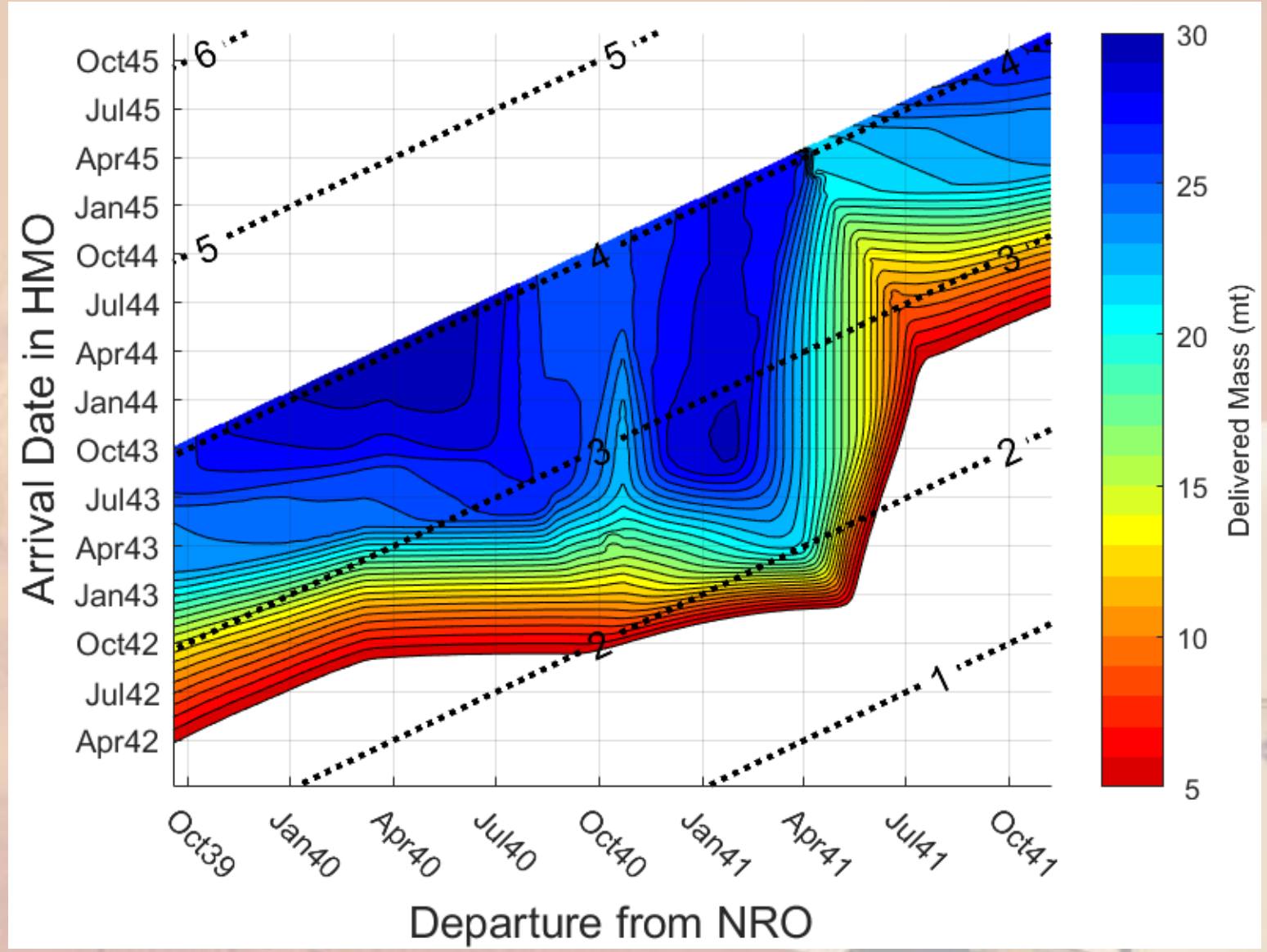


Low-Thrust Trajectory Maps – “Bacon” Plots

- Need a “roadmap” of SEP trajectories analogous to ballistic porkchop plots
- Shows **maximum delivered mass** for launch/arrival space
  - Architecture assumptions built in
  - Simulations in MALTO
- Thousands of trajectories were generated over **2038-2054**
- Created for both:
  - Earth→Mars
  - Mars→Earth

Ballistic “Porkchop” Plot



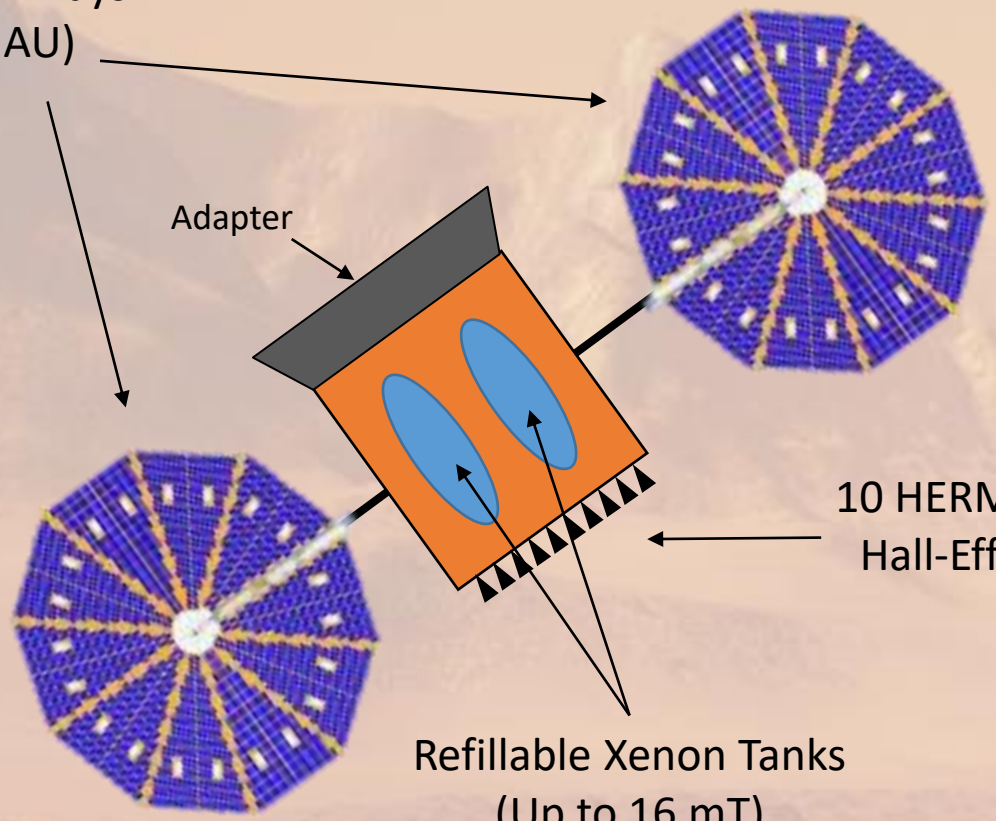


Pre-decisional. For planning and discussion purposes only.

Notional SEP Tug Assumptions

Dry Mass: 8 mT

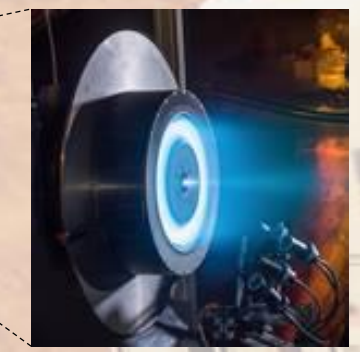
150 kW Arrays
(@ 1 AU)



10 HERMeS (ARRM*)
Hall-Effect Engines

Refillable Xenon Tanks
(Up to 16 mT)

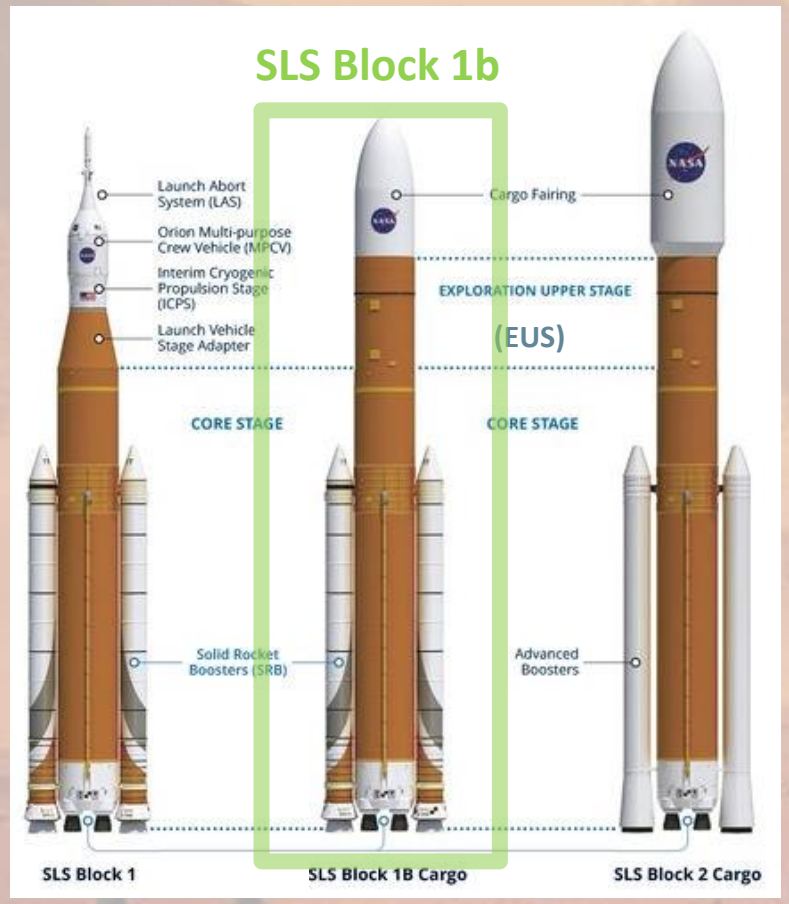
Parameter	Value	Units
Dry Mass	8	mt
Power (1 AU)	150	kW
Thruster	HERMeS	(x10)
Specific Impulse (Isp)	2660	seconds
Thrust	585 (each)	mN
Max Xenon	16	mt

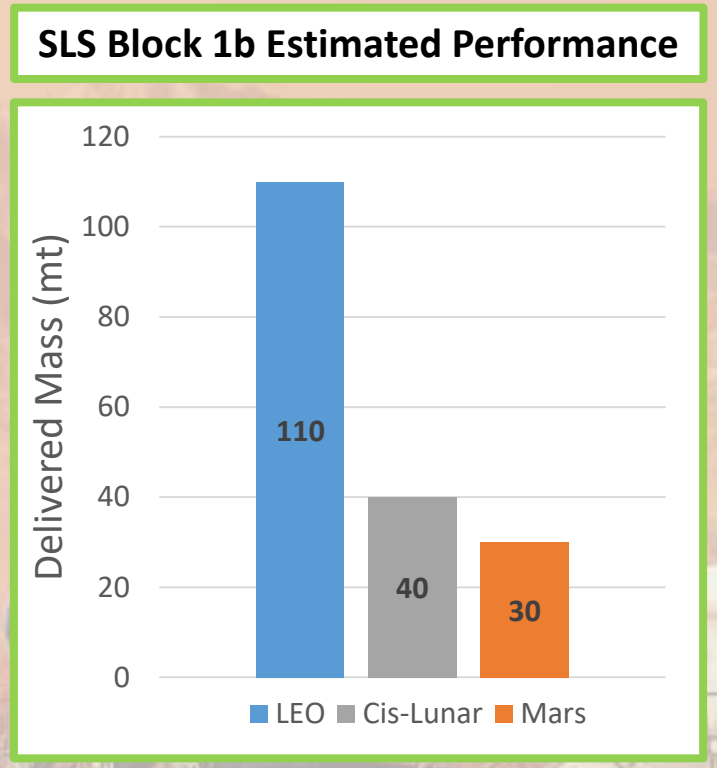


*Asteroid Redirect Robotic Mission

Launch Vehicle Assumptions

- A key building block of any Humans-to-Mars architecture is the assumed capability of a future heavy-lift launch vehicle - discretizes the whole architecture
- SLS Evolution: Block 1 (70 mT to LEO), **Block 1b (110 mT),** Block 2 (130 mT)





Orbital Resupply Concept

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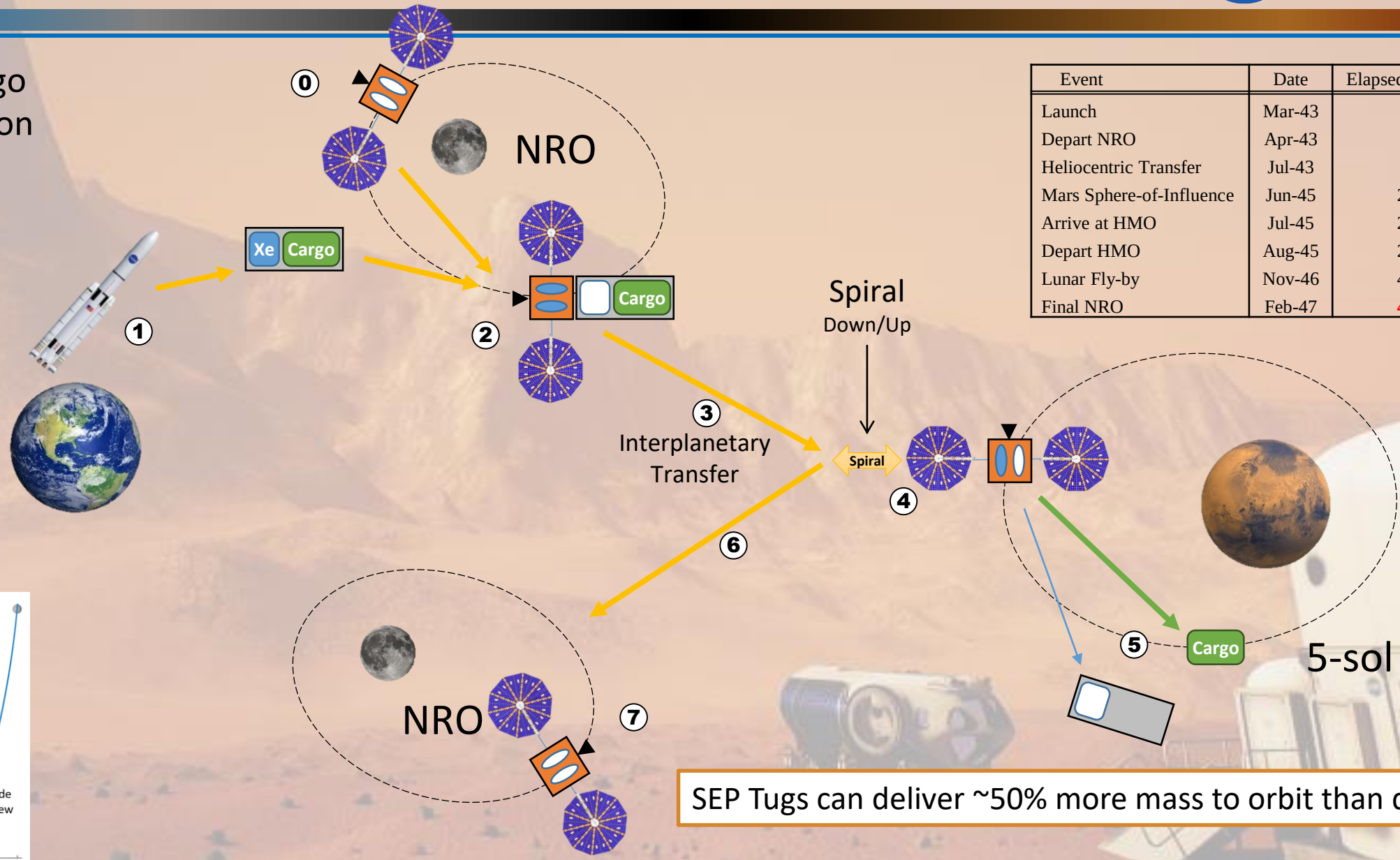
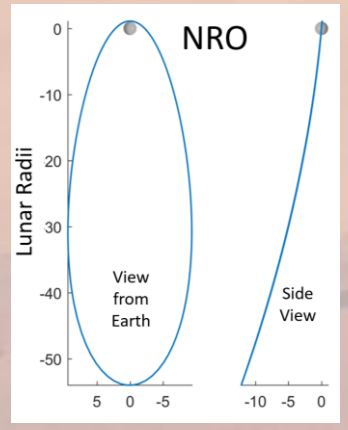
Cargo - Cargo
Xe - Xenon



Event	Date	Elapsed Months
Launch	Mar-43	0
Depart NRO	Apr-43	1
Heliocentric Transfer	Jul-43	4
Mars Sphere-of-Influence	Jun-45	27
Arrive at HMO	Jul-45	28
Depart HMO	Aug-45	29
Lunar Fly-by	Nov-46	44
Final NRO	Feb-47	47



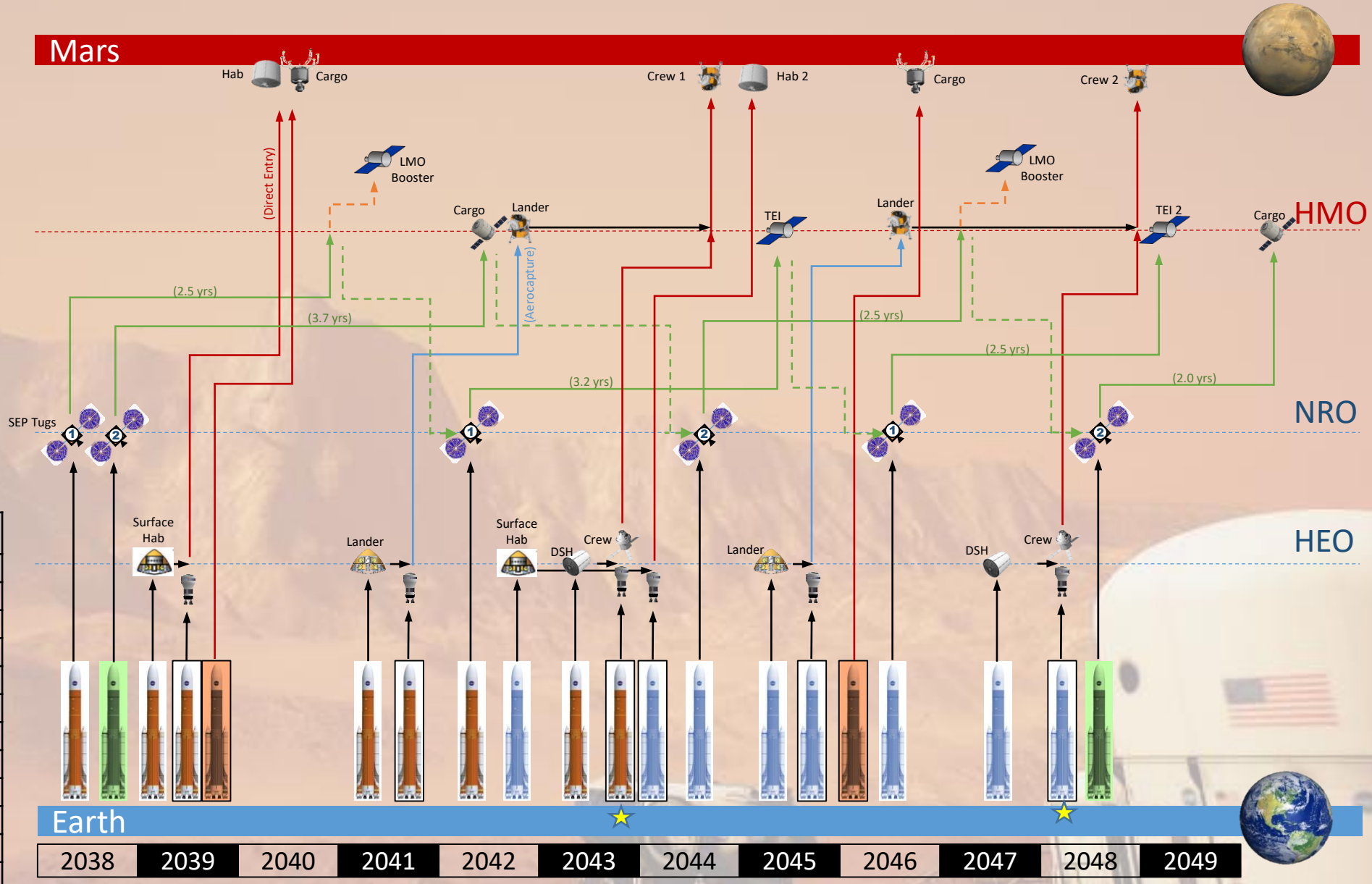
SEP Tugs can deliver ~50% more mass to orbit than direct

Pre-decisional. For planning and discussion purposes only.

Example launch sequence for a sustained human outpost

Mission element mass assumptions:

Mission Element	Mass Allocation	Includes Prop?
Crew		
Orion (Command + Service)	20 mt	yes
Deep-Space Habitat (DSH)	30 mt	no
Surface Habitat (HAB)	35 mt	no
Propulsive		
TEI Stage	26 mt	yes
MOI Stage	28 mt	yes
LMO-to-HMO Booster Stage	26 mt	yes
Crew Lander/MAV	50 mt	yes
Exploration Upper Stage (EUS)	14 mt	no
SEP Tug	8 mt	no
Resupply		
Orbital Resupply Module	15-30 mt	no
Surface Resupply Module	20-30 mt	yes

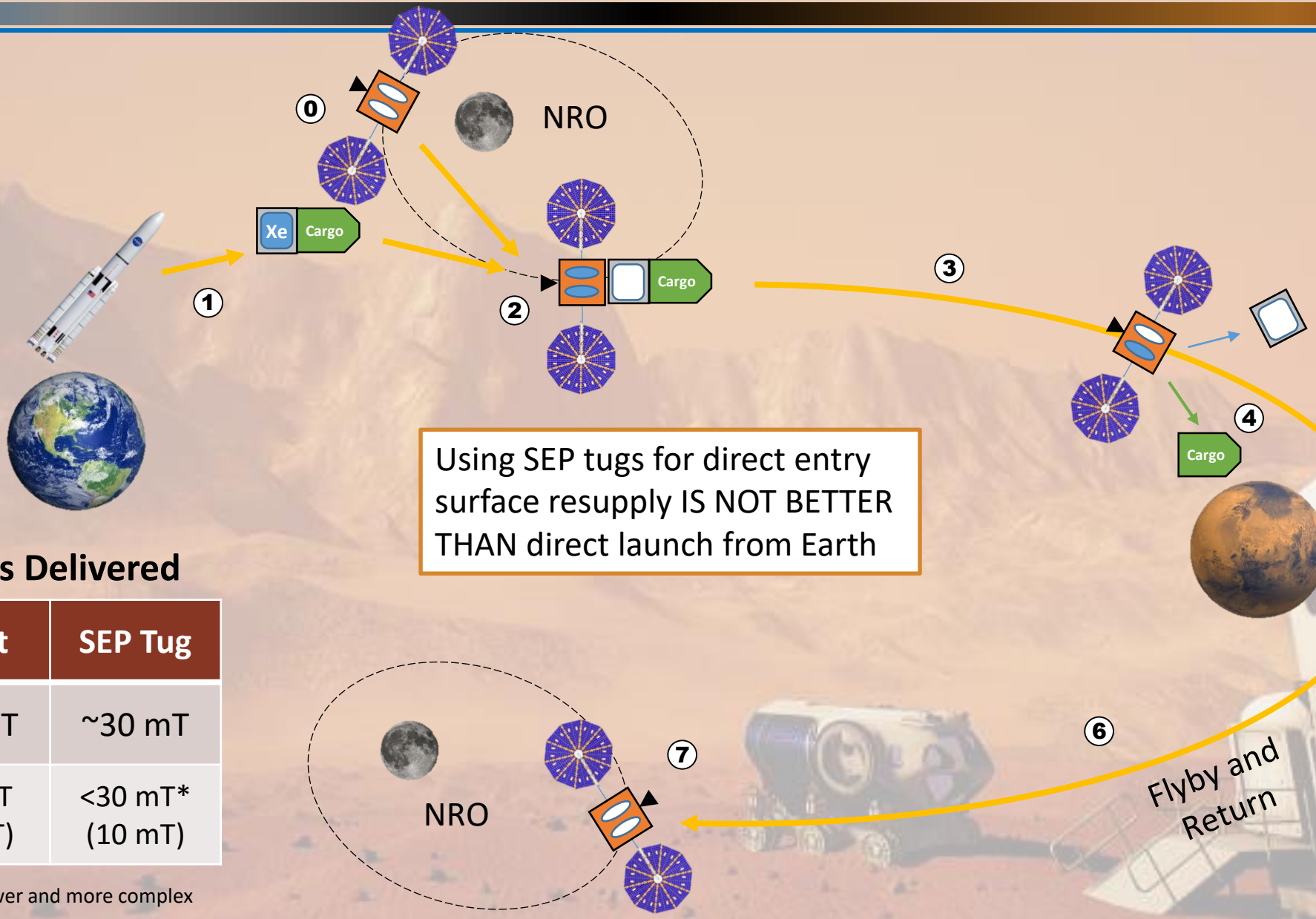


Key

- Launch associated w/ 1st expedition
- Launch associated w/ 2nd expedition
- Ballistic Trajectory Required
- Orbital Cargo Launch
- Surface Cargo Launch
- Aerobraking
- Low-Thrust Transfer
- Ballistic Transfer
- Ballistic w/ Aerocapture
- EUS
- Crewed Launch

Surface Resupply Concept

Cargo - Cargo
Xe - Xenon



Using SEP tugs for direct entry surface resupply IS NOT BETTER THAN direct launch from Earth

Maximum Mass Delivered

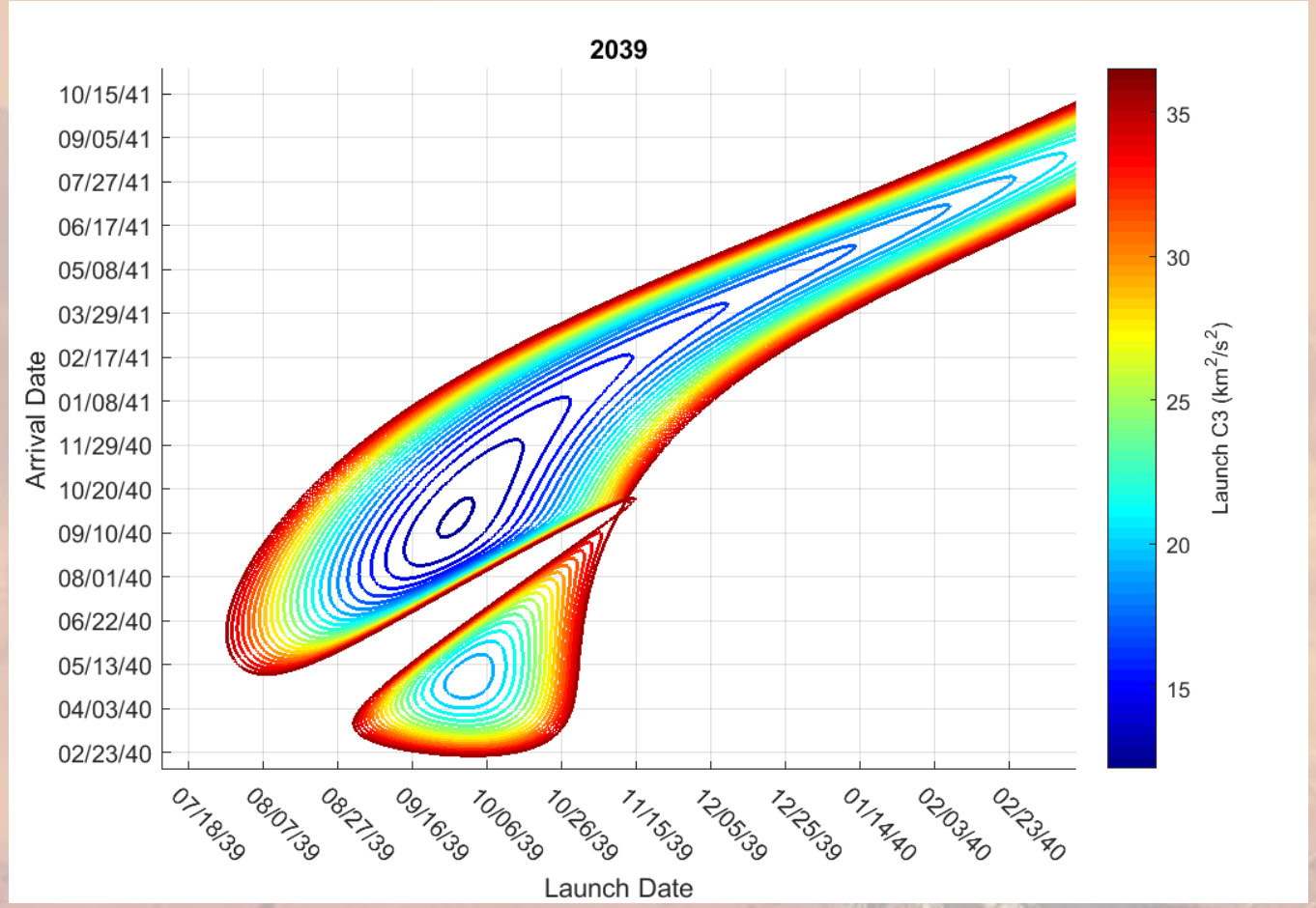
	Direct	SEP Tug
Orbit	~20 mT	~30 mT
Entry (Surface)	~30 mT (10 mT)	<30 mT* (10 mT)

*Similar mass, but much slower and more complex

Conclusions

- Sustained human presence on Mars will require a significant amount of cargo
- Solar Electric Propulsion (SEP) can be very efficient for cargo delivery
- A precursory study of the benefits of reusable SEP tugs showed that
  - Mass delivered to Mars orbit can by increased by ~50%
  - SEP tugs do not appear to be beneficial to direct entry surface cargo
- Other key findings:
  - SEP tugs are feasible using technology currently in development (eg. ARRM)
  - SEP may take longer, but it is much more flexible
  - This flexibility allows for more robust launch sequencing
- Future Work:
  - More sophisticated tools for architecture **design** and **optimization**
  - Seek better understanding of **benefits vs. disadvantages** of SEP usage

Backup


2039
Arrival Date
10/15/41
09/05/41
07/27/41
06/17/41
05/08/41
03/29/41
02/17/41
01/08/41
11/29/40
10/20/40
09/10/40
08/01/40
06/22/40
05/13/40
04/03/40
02/23/40
07/18/39
08/07/39
08/27/39
09/16/39
10/06/39
10/26/39
11/15/39
12/05/39
12/25/39
01/14/40
02/03/40
02/23/40
Launch Date
35
30
25
20
15
Launch C3 (km²/s²)